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On Obtaining Design Allowables for
Adhesives Used in the Bonded-
Composite Repair of Aircraft

Peter Chalkley and John van den Berg

DSTO-TR-0608

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Peter Chalkley and John van den Berg

**Airframes and Engines Division
Aeronautical and Maritime Research Laboratory**

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ABSTRACT

A technique is documented, along with its experimental validation, for obtaining engineering-standard design allowables for structural adhesives used in the bonded-composite repair of aircraft structure. The design of durable bonded-composite repairs is reliant on such design allowables. It is intended that allowables obtained using this technique replace the manufacturer's brochure data that is currently in use for some adhesives. Design allowables for the most common repair adhesive - FM73 - were obtained as part of the experimental validation.

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Executive Summary

Bonded composite repairs have been successfully applied to many RAAF aircraft to extend the service life of damaged airframes. The design of such repairs relies on the availability of high-quality engineering-standard material property data for all the repair constituents. This report is concerned with validating a test technique for obtaining material property data for new adhesives that might be used in bonded repair applications.

A test technique, ASTM D5656, was investigated to determine its suitability for providing engineering-standard shear stress-strain data for adhesives. The investigation involved a series of tests, performed in accordance with ASTM D5656, on the most common repair adhesive - FM73. The standard was found to be generally suitable. Some minor inconsistencies and ambiguities were found and these, along with suggested fixes, are documented in the report. The data obtained for FM73 was of engineering standard and a statistically significant number of tests (over 20) were performed at each test condition. Error estimates were found for each adhesive design allowable. This data represents a significant improvement over the existing "brochure" data provided by the manufacturer. Such brochure data does not include error estimates nor an indication of the standard followed to obtain the data.

It is intended that this report be used as a guide to obtaining shear stress-strain data for new adhesives that might be used in bonded repair. Also the data obtained for FM73 should prove useful for further bonded repair design when used in conjunction with RAAF Engineering Standard C5033: "Composite Materials and Adhesive Bonded Repairs".

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1. Introduction

The design of durable bonded composite repairs to aircraft structure relies heavily on accurate material property data for the materials used. This includes data for the adhesive used to bond the patch or reinforcement to the aircraft structure. Adhesive manufacturers usually supply data obtained by following standards such as MMM-132-A or MIL-A-25463-B. Such data is useful for ranking adhesives in terms of mechanical performance but it is shear stress-strain data that is needed for design. Manufacturers sometimes provide the shear stress-strain data needed for design - sometimes they do not. The manufacturers' data where it does exist can often be described as "brochure" data; data commonly given with no indication of its accuracy (such as the standard deviation of the property quoted) nor with any indication of the test standard followed in obtaining the data. More rigorously obtained and better documented data is needed for bonded repair design.

This report documents the techniques and standards followed in obtaining reliable, engineering standard shear stress-strain data for the structural adhesive FM73. The data obtained is for an 8 hours at 80°C cure of the adhesive (which is typical of RAAF in-field repairs) rather than the manufacturer's recommended 1 hour at 120° cure. Surface treatment of the aluminium alloy adherends prior to bonding also followed RAAF in-field repair techniques.

Material property data and bonded repair design allowables for the adhesive were obtained at 20°C (dry), -40°C (dry) and 80°C (saturated with water). The last two temperature/moisture conditions represent the extremes of the operating envelope for this adhesive.

American Society for Testing and Materials standard ASTM D5656-95 [1] was followed in obtaining the data with some exceptions as documented in this report.

2. Overview of the Test Programme

A total of 84 thick-adherend lap-shear specimens were tested to obtain shear stress-strain data for the adhesive FM 73 cured for 8 hours at 80°C. The breakdown of those tests is given in Table 2.1.

Table 2.1. Test conditions and number of specimens.

test condition	no. specimens
20°C, dry	24
-40°C, dry	30
80°C, moisturised	30

3. Overview of the Experimental Procedure

The experimental procedure followed was primarily that of ASTM D5656-95 "Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behaviour of Adhesives in Shear by Tension". This standard draws heavily on the technique developed by Raymond Krieger at Cyanamid [2] (now Cytec) for the in-situ measurement of adhesive properties. One the most important facets of Krieger's technique was the use of KGR-1 extensometers which allowed for the accurate measurement of adhesive shear deformations. These extensometers were used to obtain the data presented in this report.

A similar European standard is ISO 11003-2 "Adhesives - Determination of Shear Behaviour of Structural Bonds, Part 2: Thick-Adherend Tensile-Test Method" [3]. The ISO standard advises the use of similar extensometers. The major difference between the two standards is in the geometry of the specimen. The specimen in ISO 11003-2 has a shorter overlap length and thinner adherends than the specimen in ASTM D5656-95.

4. Specimen Manufacture

4.1 Specimen fabrication overview

Thick-adherend test specimens were individually cut from a larger bonded panel. Each panel yielded 6 specimens. Fourteen bonded panels were prepared to make a total of 84 specimens. The dimensions of the panels were 9 inches by 9 inches by $\frac{3}{4}$ of an inch (plus the adhesive thickness). Specimens, 1 inch wide, were cut from the panel and are shown Fig. 4.1.

4.2 Materials

The materials used to fabricate the specimens are listed in Table 4.2.1.

Table 4.2.1. Materials

adhesive	adherends
FM73 from Cytec	2024 -T3 aluminium alloy - 9.5 mm thick

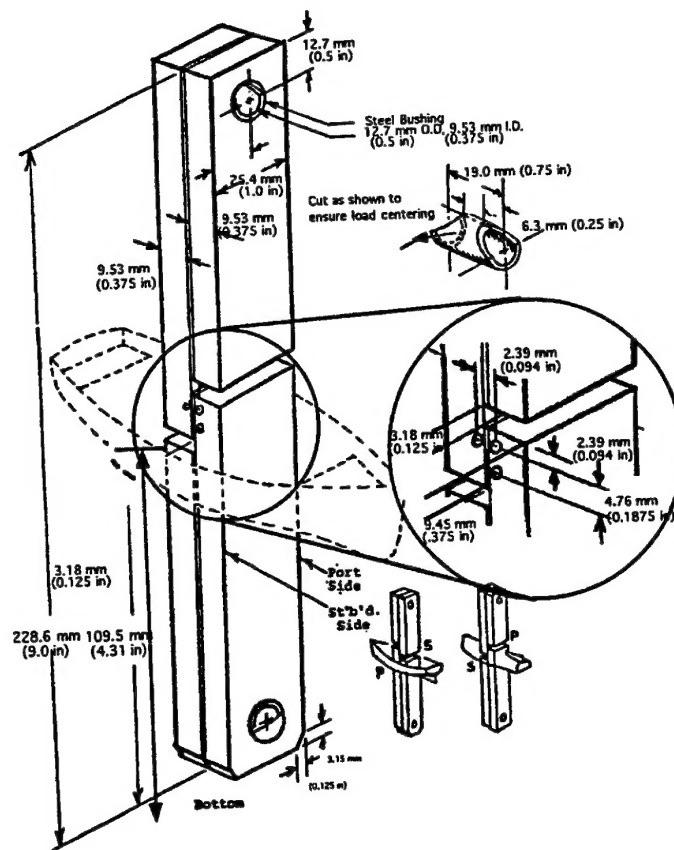


Figure 4.1. The Thick-Adherend Lap-Shear Test Specimen (taken from Ref. 2).

Table 4.2.2 lists details pertaining to the adhesive:

Table 4.2.2. Adhesive Details

adhesive	FM 73
source	Cytec
date of manufacture	7 February 1996
batch number	4903 - 01153 - 0001
form	film
areal density	0.085 lbs/sq. ft

4.3 Surface preparation

The specimens were manufactured so as to replicate typical in-field repair conditions as closely as possible. Consequently, the surface preparation of the aluminium adherend panels was as follows:

1. Prepare one percent aqueous silane coupling agent
2. Solvent clean with MEK and tissues to remove gross contamination
3. Scotch brite abrade with 3M no. 447 pad
4. Remove abrading debris using MEK with tissues wiped once in one direction and discarded
5. Wipe with distilled water soaked tissues
6. Water break test to ensure a contaminant free surface
7. Dry surface for 10 minutes using an industrial hot air gun at 80° C
8. Grit blast with 50 micron aluminium oxide grit using dry nitrogen gas as a propellant
9. Brush apply coupling agent and keep surface wet for 15 minutes
10. Dry coupling agent for 1 hour at 80°C

4.4 Bonding

The adhesive FM73 was placed between the two surface treated panels and the assembly placed in a heated platen press. The cure cycle applied to the adhesive was to heat the panel at a rate of approximately 5°C/minute to 80°C and dwell there for 8 hours before cooling. The applied pressure was approximately 100 kPa.

4.5 Machining

Specimens were machined from the panels using a milling machine. Coolant was used. The horizontal notches were cut so that a thin sliver of metal remained over the adhesive bondline. Direct contact of the coolant with adhesive was thus avoided. The specimen was removed from the milling machine, dried and then the final cut through the thin sliver of metal was made with a craft knife.

5. Experimental Procedure

5.1 ASTM D5656-95 reporting requirements

The experimental procedure followed ASTM D5656-95 requirements as closely as possible. Some exceptions were necessary and these are documented. In fact, there are some minor ambiguities and errors in the standard which are also documented. ASTM

D5656-95 stipulates the material details, test set up details and test results that are required to be reported. These are presented in Table 5.1.1.

Table 5.1.1. ASTM 5656-95 reporting requirements

Report Requirements	Section of this Report Meeting Requirement
1. Complete identification of the adhesive tested, including type, source date of manufacture, etc.	4.2 Materials - Table 4.2.2.
2. Complete identification of the adherent material used, method of cleaning, and surface preparations.	4.2 Materials - Table 4.2.1.
3. Application and cure procedures, and other pertinent conditions used in preparing the specimen.	4.3 Surface preparation, 4.4 Bonding and 4.5 Machining
4. Adhesive thickness, and bond area dimension including average length and width	5.3 Measurement of bond dimensions and APPENDIX A: Bond Dimensions
5. Conditioning prior to testing.	5.5 Specimen conditioning
6. Conditioning during testing (that is, temperature, humidity, etc).	6. Test Results - temperature subheadings
7. The shear stress (δ_{ll}) and corrected shear strain (γ_{ll}) at the linear limit (ll).	6.1.4, 6.2.4 and 6.3.4 ASTM D5656-95 report tables
8. The shear modulus (G_c).	6.1.4, 6.2.4 and 6.3.4 ASTM D5656-95 report tables
9. The shear stress (δ_{kn}) and corrected shear strain (γ_{kn}) at the knee (kn).	6.1.4, 6.2.4 and 6.3.4 ASTM D5656-95 report tables
10. The shear stress (δ_{ul}) and corrected shear strain (γ_{ul}) at sample fracture (ul).	6.1.4, 6.2.4 and 6.3.4 ASTM D5656-95 report tables
11. The nature of sample fracture (adhesive/cohesive).	6.1.3, 6.2.3 and 6.3.3 Typical failure surfaces
12. An average value for shear stress (δ_i), corrected strain (ϵ_i), and modulus (G_c) shall be determined for each group of specimen tested.	6.1.4, 6.2.4 and 6.3.4 Average property tables

5.2 Design allowables

Design allowables were obtained from the measured shear stress-strain data following the elastic/perfectly plastic idealisation method recommended by Hart-Smith [4]. The design allowables obtained using this method are listed in Table 5.2.1.

Table 5.2.1. Hart-Smith's stress strain design allowables

design allowable	symbol
"elastic" shear strain limit	γ_e
plastic shear strain	γ_p
plastic shear stress (MPa)	τ_p
strain energy density in shear (MPa)	A_s

These allowables and their relationship to an actual stress-strain curve are defined in Fig. 5.2.1.

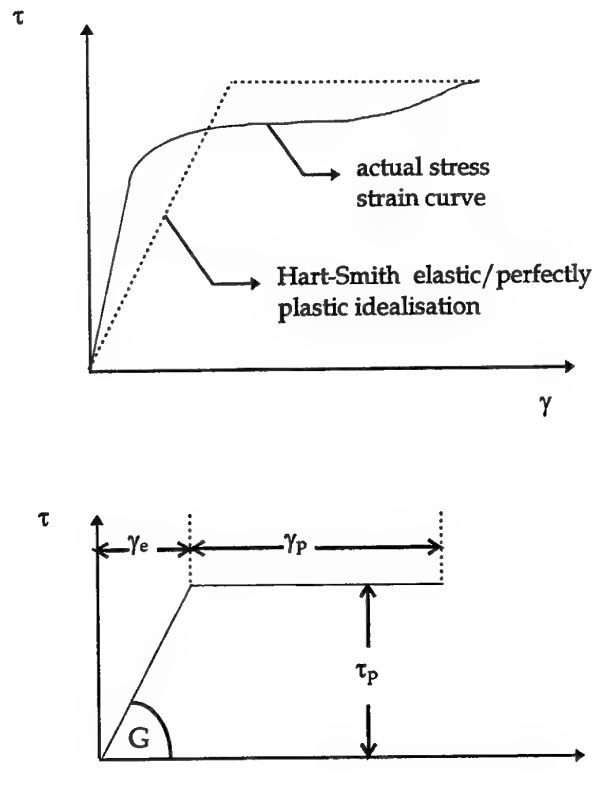


Figure 5.2.1. The Hart-Smith elastic/perfectly-plastic idealisation of the adhesive stress strain curve [4].

Note that in this idealisation, the strain energy density to failure (the area under the stress-strain curve) is identical for both the actual and the idealised curves. Hart-Smith demonstrated [4] that the failure strength of a bonded joint depends solely on the strain energy density to failure and not on the shape of the stress-strain curve. This elastic/perfectly-plastic idealisation retains the failure strength information and allows for simple mathematical analyses of joints.

5.3 Measurement of bond dimensions

The bond thickness, width and length was measured for each of the 84 lap joint specimens. Using the measured bond width and length the bond area was calculated for all specimens. According to ASTM D5656 the bond dimensions were to be measured to the levels of accuracy as set out in the Table 5.3.1.

Table 5.3.1. ASTM D5656 requirements for bondline measurement accuracy.

	imperial	metric
bond width	± 0.001 in	± 0.003 mm
bond length	± 0.001 in	± 0.003 mm
bond thickness	± 0.0001 in	± 0.0003 mm

Note that the required accuracy in metric units is much greater than that in imperial units. There are other instances in ASTM D5656 where the conversion from imperial to metric units has not been carried out correctly. All measurement in this study were made in metric units and these accuracies were found to be impractically low. As a result the width measurements were the only measurements which met these requirements in metric units. Notably though, ISO 11003-2 as well as the older American standard ASTM D3983 [5] both suggest lower accuracies than ASTM D5656. In fact, the accuracy requirements in these latter standards were all exceeded as shown in Table 5.3.2.

Table 5.3.2. A Comparison of the Accuracy Requirements and the Actual Tolerances Achieved.

	ASTM D 3983	ISO 11003-02	ASTM D 5656	Actual Tolerance
bond thickness	± 0.005 mm	± 0.01 mm	± 0.0003 mm	± 0.005 mm
bond width	± 0.5 mm	± 0.1 mm	± 0.003 mm	± 0.003 mm
bond length	± 0.5 mm	± 0.1 mm	± 0.003 mm	± 0.05 mm
bond area	± 1 mm ²	± 0.2 mm ²	± 0.005 mm ²	± 0.1 mm ²

Adhesive thickness was measured using a binocular microscope fitted with a scale in one of the eyepieces. A total of eight adhesive thickness readings were taken per specimen - four per side. Bond width was measured with a micrometer and bond length was measured using a travelling microscope. Bond dimensions for all specimens are presented in Appendix A.

5.4 Test machine control mode

ASTM D5656 is somewhat ambiguous as to whether the testing machine should be run under load control or at a set crosshead speed. Section 6 [1] states that "The machine shall be capable of maintaining a rate of loading of 2455 N/min" implying load control but then goes on to state in note 2 of the same section that "The cross-head speed setting required to approach the specified loading rate is dependent on the modulus of the adherends and the adhesive being evaluated" implying crosshead speed control.

The test machine for this study was run under displacement control, ie, a set crosshead speed was used. A previous study of FM73 showed [6] that the yield stress is strain rate dependent, that little viscoelasticity occurs and that the adhesive is almost perfectly plastic once yielded. Consequently crosshead speed control was used as this simulated strain rate control while allowing a simple means of test control.

Load control in the region in which the adhesive is almost perfectly plastic would drive the strain rate towards infinity and distorted data would result. Indeed the "knee" region reported for adhesive stress strain curves is often just an artefact of the load-control test technique.

The crosshead speeds for the three different test conditions is shown in Table 5.4.1.

Table 5.4.1. Crosshead Rates for the Three Test Conditions

test condition	crosshead rate
21°C dry	0.5 mm/min
-40°C dry	0.2 mm/min
80°C wet	0.2 mm/min

The ideal crosshead rate for the 21°C tests was 0.22 mm/min but the slowest speed the machine available at the time was doing was 0.5 mm/min. This resulted in a loading rate in the elastic regime of 5700 N/min. Because strain rate is only a second order effect the influence on the results would be small.

5.5 Specimen conditioning

The 80°C/wet specimens were moisturised in a hot water bath operating at 50°C and 95% relative humidity for 10 months prior to testing. The average moisture content was estimated to be 0.8%.

5.6 Test machines and temperature control

Instron static tensile test machines were used to test the specimens. An Instron 1185 100kN machine was used primarily. The hot and cold temperatures were applied using an Instron environment chamber. The -40°C test temperature was achieved by cooling with liquid nitrogen pressure fed with gaseous nitrogen. Temperature was measured with the use of a digital thermometer sensing via a type K thermocouple, applied directly to the specimen.

5.7 Calibration of transducers

Three transducers were used in the testing: a load cell and the two Krieger extensometers. The load cell is calibrated to NATA standard A. The Krieger KGR-1 extensometers were calibrated using a micrometer head mounted on a purpose designed shear displacement rig. The micrometer head is also calibrated to NATA standard A.

5.8 Specimen alignment

In order to ensure that the applied loads on the specimen were in tension and to preclude any out of plane bending the load train to which the specimens were fixed had universal joints incorporated at each end of the specimen and were attached using close tolerance sliding pins.

5.9 Data acquisition and generation of graphs

Data was acquired in real time during the test using a computerised data acquisition system using Labtech notebook software to record the load, time and the two extensometer readings as well as displaying a load strain graph. After the test the data was analysed using the software Origin.

6. FM73 Test Results

6.1 Room temperature results

6.1.1 Metal deformation factor

The metal deformation factor [1,2,3] for the room temperature tests was measured to be 1.0373×10^{-4} mm/kN.

6.1.2 Typical room temperature shear stress-strain curve

Fig. 6.1.2.1 shows a typical room temperature shear stress-strain curve and its elastic/perfectly plastic idealisation.

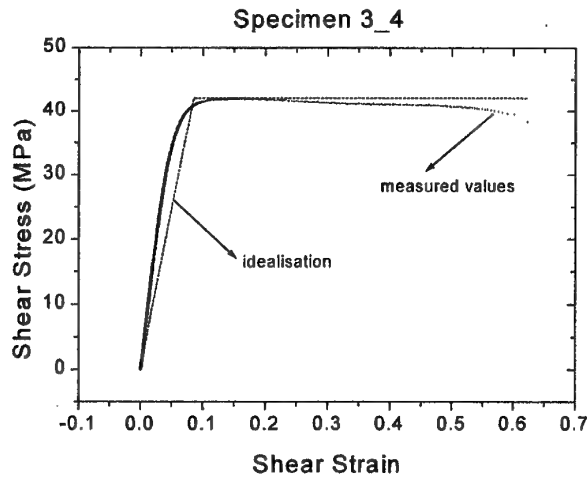


Figure 6.1.2.1 Typical room temperature shear stress-strain curve.

Fig 6.1.2.1 shows that the room temperature stress-strain curve is almost elastic/perfectly plastic and that the Hart-Smith idealisation is reasonably faithful to this curve.

6.1.3 Typical room temperature failure surface

Fig. 6.1.3.1 shows a typical room temperature test failure surface.

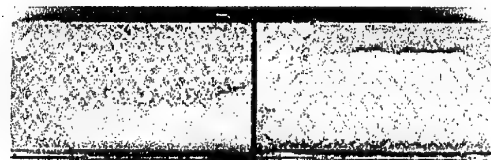


Figure 6.1.3.1. Typical failure surface for room temperature specimens.

All of the room temperature test specimens exhibited a failure locus close to one/both of the aluminium adherend surfaces. However, this was not widespread total adhesive failure as large areas have the criss-cross impression of the scrim on the aluminium side and roughened adhesive on the other side. Total adhesive failure, characterised by a smooth adhesive surface on one adherend and a smooth aluminium surface on the other adherend, did occur in some areas.

6.1.4 ASTM D5656 report table

Table 6.1.4.1. ASTM D5656 report table for the room temperature properties.

Specimen Number	G_c (MPa)	δ_{II} (MPa)	γ_{II}	δ_{kn} (MPa)	γ_{kn}	G_{kn} (MPa)	δ_{ul} (MPa)	γ_{ul}
6_3	807	27.17	0.0363	39.71	0.0758	524	39.68	0.5569
8_4	809	27.27	0.0372	39.51	0.0782	505	40.67	0.5521
9_4	775	27.37	0.0380	38.33	0.0726	528	37.98	0.6068
10_3	745	27.27	0.0396	38.53	0.0774	498	37.24	0.6181
9_3	762	27.45	0.0380	38.73	0.0726	533	39.16	0.5984
7_3	787	28.52	0.0388	39.41	0.0734	537	40.11	0.6367
13_3	779	26.20	0.0357	40.49	0.0718	564	37.37	0.6378
10_4	818	27.65	0.0372	38.53	0.0710	545	39.90	0.6285
11_3	793	27.17	0.0363	39.22	0.0718	546	39.57	0.5588
7_4	789	26.40	0.0357	38.63	0.0750	515	39.92	0.5658
8_3	749	27.07	0.0388	39.02	0.0820	476	39.92	0.6348
11_4	769	27.17	0.0388	40.00	0.0750	533	40.00	0.6115
3_4	805	29.38	0.0380	38.30	0.0730	525	38.30	0.62234
5_3	765	25.14	0.0357	36.30	0.0726	500	36.30	0.5633
12_4	797	29.20	0.0396	39.18	0.0702	558	39.18	0.5207
1_4	796	26.20	0.0348	38.09	0.0770	497	38.09	0.6093
12_3	857	26.89	0.0340	40.03	0.0702	570	40.03	0.5413
14_3	849	24.37	0.0317	39.64	0.0734	540	39.64	0.4345
6_4	869	28.42	0.0340	40.81	0.0718	568	40.81	0.5380
5_4	829	26.97	0.0340	34.16	0.0739	462	34.16	0.5615
4_4	850	28.52	0.0357	41.07	0.0740	555	41.07	0.5494
3_3	887	28.10	0.0320	41.44	0.0740	560	41.44	0.5682
4_3	833	28.90	0.0363	41.49	0.0726	571	41.49	0.5657

Averages and standard deviations from the data for the 23 specimens above is presented in Table 6.1.4.2.

Table 6.1.4.2. Adhesive property averages and standard deviations for the room temperature tests.

δ_{II} (MPa)	27.34 \pm 1.21
γ_{II}	0.0364 \pm 0.0022
G_c (MPa)	805.47 \pm 38.84
δ_{kn} (MPa)	39.22 \pm 0.96
γ_{kn}	0.0739 \pm 0.0028
δ_{ul} (MPa)	39.14 \pm 1.76
γ_{ul}	0.5774 \pm 0.0475

6.1.5 Room temperature design allowables

The room temperature design allowables were calculated following Hart-Smith's method [4]. The results are presented in Table 6.1.5.1. The plastic shear stress was taken to be the maximum shear stress on the stress-strain curve.

Table 6.1.5.1. Room temperature design allowables.

specimen number	γ_e	G (MPa)	τ_p (MPa)	γ_p	A_s (MPa)
6_3	0.0739	537	41.87	0.4830	21.77
8_4	0.0749	543	42.32	0.4772	21.78
9_4	0.0805	472	40.65	0.5263	23.03
10_3	0.0802	465	40.50	0.5379	23.41
9_3	0.0768	510	40.93	0.5216	22.92
7_3	0.0758	529	41.65	0.5609	24.94
13_3	0.1000	374	42.65	0.5378	25.07
10_4	0.0786	507	40.65	0.5499	23.95
11_3	0.0732	540	41.69	0.4856	21.77
7_4	0.0757	528	40.95	0.4901	21.62
8_3	0.0733	545	40.96	0.5615	24.50
11_4	0.0771	519	41.80	0.5344	23.95
3_4	0.0854	449	42.03	0.5370	24.36
5_3	0.1202	302	38.91	0.4431	19.58
12_4	0.0740	529	41.35	0.4467	20.00
1_4	0.0875	435	41.34	0.5218	23.38
12_3	0.0710	564	42.19	0.4703	21.34
14_3	0.0680	583	40.75	0.3665	16.32
6_4	0.0706	578	42.57	0.4674	21.40
5_4	0.1247	274	40.81	0.4368	20.37
4_4	0.0663	619	42.77	0.4831	22.08
3_3	0.0706	587	43.18	0.4976	23.01
4_3	0.0711	584	42.44	0.4946	22.50

Average design allowables are presented in Table 6.1.5.2.

Table 6.1.5.2. Average room temperature design allowables.

	Average	standard deviation
γ_e	0.0804	0.0151
G (MPa)	503	88
τ_p (MPa)	41.52	0.97
γ_p	0.4970	0.0468
Δ_s (MPa)	22.31	2.00

6.2 -40°C results

6.2.1 Metal deformation factor

The metal deformation factor for the -40°C tests was measured at 8.9×10^{-5} kN/mm.

6.2.2 Typical -40°C shear stress-strain curve

A typical shear stress-strain curve and its idealisation for the -40°C series of tests is presented in Fig. 6.2.2.1.

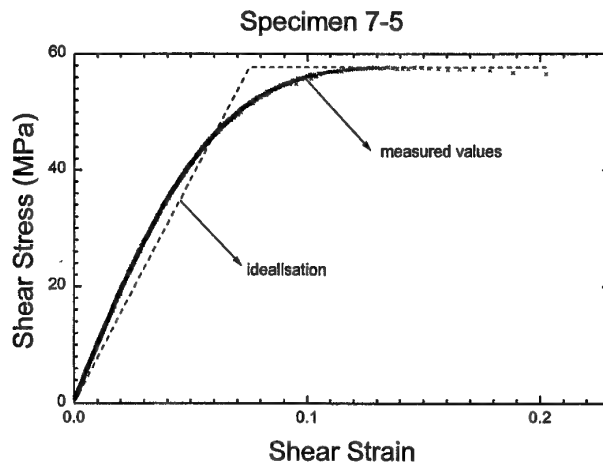


Figure 6.2.2.1. Typical -40°C shear stress strain curve.

Fig. 6.2.2.1 shows a more pronounced "knee" region than the room temperature data though the fidelity of the idealisation to the measured stress-strain curve is reasonable.

6.2.3 Typical -40°C failure surface

Fig. 6.2.3.1 depicts a typical -40°C test fracture surface.

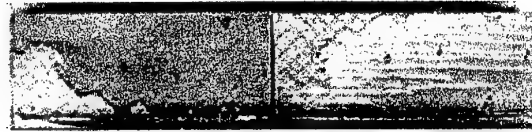


Figure 6.2.3.1 Typical -40°C fracture surface.

Surfaces from the series of -40°C tests typically showed failure around the interface between the adhesive and the aluminium adherend. Roughening of most of the adhesive surface can be seen however and it is clear that little of the failure was due to loss of adhesion.

6.2.4 ASTM D5656 report table

Table 6.2.4.1 comprises the ASTM D5656 report values.

Table 6.2.4.1. ASTM D5656 report table for the -40°C results.

Specimen number	G_c (MPa)	τ_{LL} (MPa)	γ_{LL}	τ_{kn} (MPa)	γ_{kn}	G_{kn} (MPa)	δ_{ul} (MPa)	γ_{ul}
1-5	1005	28.49	0.0283	50.0	0.066	756	56.12	0.1488
1-6	1044	20.37	0.0350	47.0	0.053	886	54.03	0.1897
3-5	914	23.25	0.0250	49.0	0.071	680	54.04	0.1426
3-6	965	24.96	0.0260	48.0	0.066	705	53.15	0.1358
4-5	939	25.48	0.0270	52.0	0.070	743	56.74	0.2859
4-6	890	35.25	0.0390	54.5	0.072	756	59.79	0.2375
5-6	831	29.37	0.0350	49.0	0.077	636	54.65	0.1736
6-5	939	24.26	0.0260	49.0	0.068	720	54.43	0.1537
6-6	808	33.78	0.0410	51.5	0.081	635	56.87	0.1983
7-5	938	20.341	0.0220	51.0	0.072	708	56.57	0.2025
7-6	922	29.51	0.0320	48.0	0.068	705	53.82	0.1993
8-5	859	31.85	0.0370	49.5	0.076	651	54.44	0.1677
8-6	1410	27.06	0.0190	55.0	0.055	1000	59.56	0.1959
9-5	925	26.72	0.0290	48.5	0.070	692	54.55	0.1752
9-6	1066	30.02	0.0280	51.0	0.068	750	57.68	0.1611
14-4	940	30.25	0.0320	52.0	0.070	742.8	58.81	0.2028

Average values are presented in Table 6.2.4.2.

Table 6.2.4.2. Average adhesive mechanical properties at -40°C .

δ_{II} (MPa)	27.23 ± 4.72
γ_{II}	0.0302 ± 0.0068
G_c (MPa)	959 ± 150
δ_{kII} (MPa)	50.27 ± 2.45
γ_{kII}	0.0688 ± 0.0079
δ_{ul} (MPa)	55.71 ± 2.14
γ_{ul}	0.1870 ± 0.0415

6.2.5 -40°C design allowables

Design allowables obtained using Hart-Smith's method are presented in Table 6.2.5.1.

Table 6.2.5.1. -40°C design allowables.

specimen number	γ_e	G (MPa)	τ_p (MPa)	γ_p	A_s (MPa)
1-5	0.0689	817	56.33	0.0930	7.18
1-6	0.0612	913	55.87	0.0991	7.25
3-5	0.0740	747	55.29	0.0860	6.80
3-6	0.0658	810	53.33	0.0910	6.61
4-5	0.0785	728	57.14	0.1356	9.99
4-6	0.0835	726	60.60	0.1731	13.02
5-6	0.0793	691	54.81	0.1181	8.65
6-5	0.0704	775	54.59	0.1044	7.62
6-6	0.0822	698	57.34	0.1406	10.42
7-5	0.0752	767	57.68	0.1273	9.51
7-6	0.0696	787	54.72	0.1408	9.61
8-5	0.0763	733	55.92	0.1001	7.73
8-6	0.0555	1087	60.30	0.1404	10.14
9-5	0.0721	763	55.04	0.1224	8.72
9-6	0.0652	878	57.22	0.1210	8.79
14-4	0.0728	820	59.74	0.1300	9.94

Averages for this data are presented in Table 6.2.5.2.

Table 6.2.5.2 Average -40°C design allowables.

	Average	standard deviation
γ_e	0.0723	0.0082
G (MPa)	791	107
τ_p (MPa)	56.46	2.15
γ_p	0.1192	0.0261
A_s (MPa)	8.81	1.85

6.3 80°C/wet results

6.3.1 Metal deformation factor

The metal deformation for the 80°C/wet tests was found to be 2.3×10^{-4} kN/mm.

6.3.2 Typical 80°C/wet shear stress-strain curve

A typical 80°C/wet shear stress-strain curve and its elastic/perfectly plastic idealisation is shown in Fig. 6.3.2.1.

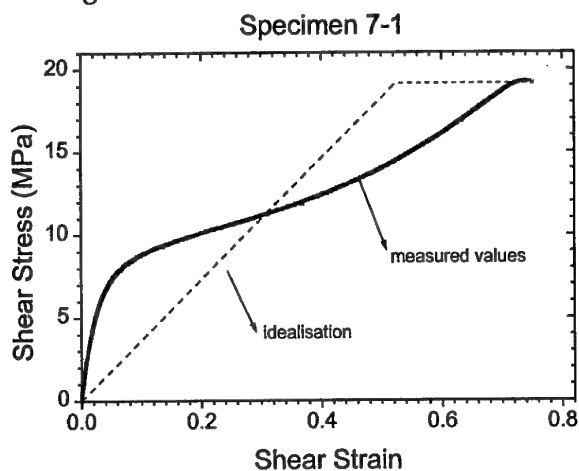


Figure 6.3.2.1. A typical 80°C/wet stress-strain curve and its idealisation.

Fig. 6.3.2.1 shows that the adhesive hardens significantly in the plastic region (in contrast to the other test conditions) as the strain increases. This hardening, of course, adds to the strain energy to failure. The elastic/perfectly plastic idealisation deviates most from the true stress-strain curve for the 80°C/wet test condition. While this

most from the true stress-strain curve for the 80°C/wet test condition. While this deviation has no effect on calculated joint strengths in the design process it may affect the calculation of stress intensity factors in the repair of cracks in metallic components. A bilinear idealisation might be more appropriate in this case.

A bilinear idealisation is shown in Fig. 6.3.2.2. It has the same strain energy to failure as the measured stress-strain curve and its initial slope is that of G_{kn} .

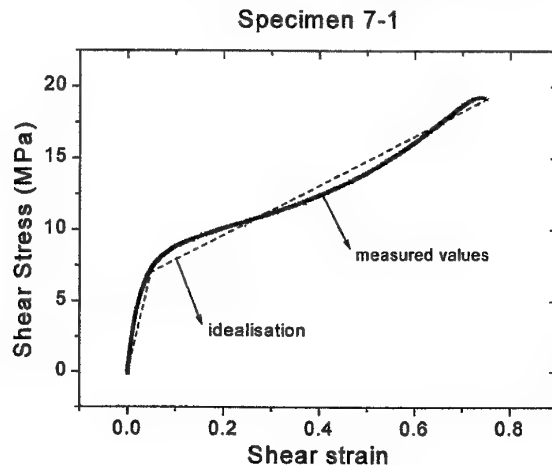


Figure 6.3.2.1. A typical 80°C/wet stress-strain curve and its bilinear idealisation.

The bilinear idealisation shows more fidelity to the measured stress-strain curve.

6.3.3 Typical 80°C/wet failure surface

A typical failure surface from the series of 80°C/wet tests is presented in Fig. 6.3.3.1.

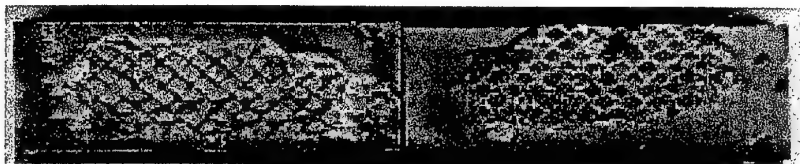


Figure 6.3.3.1. Typical 80°C/wet fracture surface.

Fig. 6.3.3.1, from a 80°C/wet test, shows a central region of desirable failure features - the criss-cross pattern of the scrim left on the aluminium surface and the corresponding roughening of the adhesive surface on the other side - but it also shows an outer ring of less desirable adhesive failure. This outer ring is presumably related to the profile of moisture diffusion in the bond region. The concentration of moisture is highest at the edge of the bonded region and decreases towards the centre. Consequently, the edges are degraded by moisture first leading to the loss of adhesion there.

6.3.4 ASTM D5656 report table

Table 6.3.4.1. ASTM 5656 report table for the 80°C/wet results.

specimen no.	G _c (MPa)	τ_{II} (MPa)	γ_{II}	τ_{kn} (MPa)	γ_{kn}	G _{kn} (MPa)	δ_{ul} (MPa)	γ_{ul}
1_1	219	6.59	0.030	8.8	0.06	147	23.49	0.9581
1_3	294	4.30	0.014	7.9	0.05	158	21.20	0.9139
2_1	288	7.14	0.024	9.6	0.053	181	24.54	0.9485
2_3	224	4.48	0.020	8	0.06	133	21.98	0.8764
3_1	240	5.15	0.021	8.9	0.06	148	22.29	0.8787
3_2	426	10.22	0.023	13.9	0.05	278	24.56	0.9420
4_1	162	2.47	0.015	5.2	0.06	87	20.16	0.9027
4_2	568	16.8	0.029	19.8	0.05	396	26.84	0.7923
5_1	55	1.69	0.030	3.11	0.072	43	7.76	0.6065
6_1	212	3.64	0.017	6.1	0.049	124	18.63	0.5334
6_2	156	3.15	0.019	5.8	0.06	97	18.78	0.8598
7_1	265	3.86	0.014	7.2	0.05	144	19.26	0.7429
7_2	269	5.85	0.020	8.7	0.055	158	26.26	0.8547
8_1	307	5.81	0.018	9.2	0.051	180	22.22	0.8893
8_2	327	5.23	0.016	7.6	0.042	180	19.94	0.7703
9_1	184	5.46	0.029	8.7	0.07	124	22.7	0.8541
9_2	2.89	5.28	0.018	7.9	0.045	175	21.08	0.8726
10_2	303	5.59	0.018	8.4	0.049	171	21.26	0.8324
11_1	351	6.74	0.019	9.0	0.044	204	23.00	0.8896
11_2	281	7.62	0.027	10.0	0.055	181	23.70	0.9242
12_1	351	6.43	0.018	8.9	0.045	197	21.52	0.9022
12_2	335	7.67	0.022	10.3	0.050	206	23.70	0.8943
13_1	496	8.24	0.016	10.3	0.035	295	22.30	0.8331
13_2	540	5.76	0.011	11.8	0.043	274	24.96	0.9031
14_1	378	8.73	0.023	11.7	0.050	234	25.61	0.9449
14_2	116	2.36	0.020	5.2	0.071	732	21.41	0.9421

Averages of the data above are presented in Table 6.3.4.2.

Table 6.3.4.2. Average adhesive mechanical properties at 80°C/wet.

δ_{II} (MPa)	5.97 \pm 2.95
γ_{II}	0.0207 \pm 0.0054
G_c (MPa)	278 \pm 134
δ_{kn} (MPa)	8.95 \pm 3.11
γ_{kn}	0.0546 \pm 0.0121
δ_{ul} (MPa)	21.85 \pm 3.83
γ_{ul}	0.8630 \pm 0.1013

6.3.5 80°C/wet design allowables

Design allowables obtained using Hart-Smith's method are presented in Table 6.3.5.1.

Table 6.3.5.1. 80°C/wet design allowables.

Specimen number	γ_e	G (MPa)	τ_p (MPa)	γ_p	A_s (MPa)
1_1	0.7539	30.3	22.82	0.1796	12.70
1_2	0.7630	30.9	23.54	0.2043	13.79
1_3	0.5449	39.0	21.24	0.3768	13.79
2_1	0.7670	32.1	24.59	0.1887	14.07
2_3	0.7420	32.4	24.04	0.1136	11.65
3_1	0.6749	33.1	22.37	0.2142	12.34
3_2	0.5751	42.7	24.56	0.3700	16.15
4_1	0.8417	23.9	20.15	0.0680	9.85
4_2	0.2716	98.8	26.84	0.5207	17.62
5_1	0.5120	15.2	7.76	0.0945	2.72
6_1	0.5064	36.9	18.71	0.0274	5.25
6_2	0.7361	25.6	18.82	0.1330	9.43
7_1	0.5243	36.5	19.15	0.2266	9.36
7_2	0.6999	33.2	23.25	0.1593	11.84
8_1	0.6616	33.6	22.22	0.2277	12.41
8_2	0.6512	30.7	19.96	0.1188	8.87
9_1	0.6694	33.9	22.67	0.1933	11.97
9_2	0.7159	29.5	21.11	0.1598	10.93
10_2	0.6427	33.2	21.32	0.1979	11.07

Specimen number	γ_e	G (MPa)	τ_p (MPa)	γ_p	A _s (MPa)
11_1	0.7223	32.0	23.08	0.1718	12.30
11_2	0.7088	33.4	23.64	0.2209	13.60
12_1	0.6852	31.4	21.49	0.2200	12.09
12_2	0.6768	35.0	23.70	0.2211	13.26
13_1	0.6115	36.5	22.30	0.2216	11.76
13_2	0.6190	39.0	24.11	0.2865	14.37
14_1	0.6950	36.9	25.63	0.2604	15.58
14_2	0.8914	24.2	21.57	0.0601	10.91

Data averages are presented in Table 6.3.5.2.

Table 6.3.5.2. Average 80°C/wet design allowables.

	Average	standard deviation
γ_e	0.6616	0.1214
G (MPa)	34.8	13.9
τ_p (MPa)	21.88	3.46
γ_p	0.2014	0.1035
A _s (MPa)	11.84	3.07

Bilinear idealisations were also performed for this set of data. Fig. 6.3.5.1 shows the technique used to obtain the bilinear idealisation.

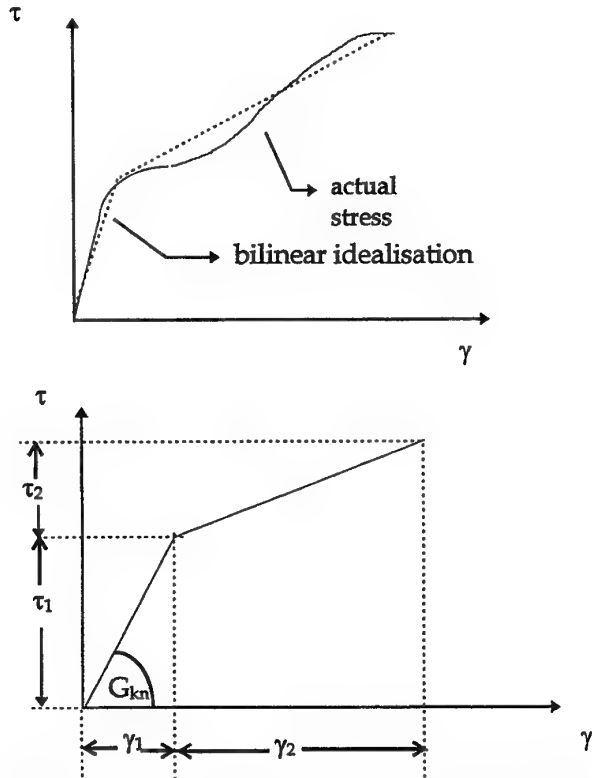


Figure 6.3.5.1. The bilinear idealisation of the adhesive stress strain curve.

Table 6.5.3 contains the bilinear-idealisation data set .

Table 6.3.5.3. *The 80°C/wet bilinear idealisation data set.*

specimen number	τ_1 (MPa)	γ_1	τ_2 (MPa)	γ_2
1_1	5.27	0.0359	17.55	0.8976
1_2	6.56	0.0654	16.98	0.9019
1_3	10.17	0.0643	11.07	0.8574
2_1	5.66	0.0313	18.93	0.9244
2_3	4.05	0.0304	19.99	0.8252
3_1	6.49	0.0439	15.88	0.8452
3_2	10.61	0.0382	13.95	0.9069
4_1	2.02	0.0234	18.13	0.8863
4_2	19.29	0.0487	7.55	0.7436
5_1	1.72	0.0400	6.04	0.5665
6_1	1.34	0.0108	17.37	0.5230
6_2	3.71	0.0384	15.11	0.8307
7_1	7.02	0.0488	12.13	0.7021
7_2	5.20	0.0329	18.05	0.8263
8_1	6.61	0.0367	15.61	0.8526
8_2	3.60	0.0200	16.36	0.7500
9_1	6.45	0.0520	16.22	0.8107
9_2	4.47	0.0255	16.64	0.8502
10_2	5.89	0.0345	15.43	0.8061
11_1	5.08	0.0249	18.00	0.8692
11_2	6.53	0.0361	17.11	0.8936
12_1	5.94	0.0301	15.55	0.8751
12_2	6.69	0.0325	17.01	0.8654
13_1	6.52	0.0221	15.78	0.8110
13_2	8.45	0.0308	15.66	0.8747
14_1	7.89	0.0337	17.74	0.9217
14_2	1.41	0.0019	20.16	0.9496

Data averages are presented in Table 6.3.5.4.

Table 6.3.5.4. Average 80°C/wet bilinear design allowables.

	Average	standard deviation
γ_1	0.0346	0.0140
τ_1 (MPa)	6.10	3.53
γ_2	0.8284	0.0997
τ_2 (MPa)	15.78	3.28

7. Summary

Documented in this report is a technique, primarily that of ASTM D5656-95, that can be followed to obtain reliable, engineering-standard, shear stress-strain data for adhesives. Such shear stress-strain data has been obtained for the structural adhesive FM73, cured under the in-field conditions of 8 hours at 80°C at 101 kPa, at three test conditions (-40°C, 21°C and 80°C/wet).

Sections 4 and 5 detail the manufacturing and surface treatment procedures that should be followed in the preparation of samples and also the method for obtaining design allowables. Section 6 documents the test data and design allowables from the three test conditions.

An average and a standard deviation is provided for each design allowable and so a measure of scatter of the data is provided that is generally not available from manufacturer's brochure data. Such measures of accuracy are essential for designing durable bonded repairs.

8. References

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2. Krieger, R., "Stiffness characteristics of structural adhesives for stress analysis in hostile environments", American Cyanamid Company, Bloomingdale Plant, Havre de Grace, Maryland, USA.
3. ISO 11003-2, "Adhesives - determination of shear behaviour of structural bonds: Part 2 - Thick-adherend tensile-test method", International Organisation for Standardisation, Geneva, Switzerland, 1993.

4. Hart-Smith, L. J., "Adhesive-bonded double-lap joints", NASA CR 112235, Douglas Aircraft Company, McDonnell Douglas Corporation, Long Beach, California, USA, 1973.
5. ASTM D3983-93, "Measuring strength and shear modulus of nonrigid adhesives by the thick-adherend tensile-lap specimen", American Society for Testing and Materials, West Conshohocken, PA, USA, 1996.
6. Chalkley, P. D. and Chiu, W. K., "An improved method for testing the shear stress/strain behaviour of adhesives", Int. J. Adhesion and Adhesives, Vol. 13, no. 4, 1993.

Appendix 1

Adhesive Thickness for Each Specimen

Thickness Measurements in graduands	Specimen Number											
	1_1	1_2	1_3	1_4	1_5	1_6	2_1	2_2	2_3	2_4	2_5	2_6
t1	30	29	31	30	28	24	31	31	32.5	30	27.5	23
t2	29.5	29	30.5	29	27.5	24.5	30	30	32	31	28	23
t3	29	30	29	30	27	24.5	31	32	32	31	28	23
t4	28	29.5	31	31	30	28.5	29	31.5	33	33	31	27
t5	27.5	29.5	30	31	30	28	28.5	31	32	32.5	31	27
t6	28	29	31	30	29.5	27.5	29	31	32	32	30	27.5
Average Thickness												
in mm	0.3373	0.3451	0.3578	0.3549	0.3373	0.3078	0.3500	0.3657	0.3794	0.3716	0.3441	0.2951

Thickness Measurements in graduands	Specimen Number											
	3_1	3_2	3_3	3_4	3_5	3_6	4_1	4_2	4_3	4_4	4_5	4_6
t1	29	28	31	31.5	30	28	29	31.5	31	30.5	28	28
t2	30	28	32	30	30	28	29.5	30	32	30	28	28.5
t3	29	28	30.5	32	30	27	29.5	31	31	30	28	29
t4	27	31	32.5	33	32.5	30	28.5	33	31	32	29.5	29
t5	26	31	32.5	32	32	30	27	28	31	32	28	28
t6	26	31	32	32	33	30	27	28	31	31.5	30	27.5
Average Thickness												
in mm	0.3275	0.3471	0.3735	0.3735	0.3676	0.3392	0.3343	0.3559	0.3667	0.3647	0.3363	0.3333

Note:- 1 graduand is approximately equivalent to 1 / 85 mm

Adhesive Thickness for Each Specimen

Thickness Measurements in graduands	Specimen Number											
	5_1	5_2	5_3	5_4	5_5	5_6	6_1	6_2	6_3	6_4	6_5	6_6
t1	29	30	29.5	29	27	22	27	28	28	27.5	27.5	26
t2	29.5	30.5	30	29.5	26.5	22.5	26	28	27	28	27	26.5
t3	29	29	29.5	29.5	26.5	22	27	27	27	28	27.5	26
t4	26.5	29	30	30	29	26.5	28	27	27	27	28	27
t5	27	29	31	29	27	27	28.5	27	27	27.5	28	27
t6	26.5	28.5	30	30	28	27	28	26.5	27.5	27.5	28	27
Average Thickness												
in mm	0.3284	0.3451	0.3529	0.3471	0.3216	0.2882	0.3225	0.3206	0.3206	0.3245	0.3255	0.3127

Thickness Measurements in graduands	Specimen Number											
	7_1	7_2	7_3	7_4	7_5	7_6	8_1	8_2	8_3	8_4	8_5	8_6
t1	26	28	26	28.5	25	24.5	27	29	29	28	25	28
t2	26	27	27	29	26	24	28	29	28	28	25	27.5
t3	26	27	27	28.5	25	23.5	28.5	29	28.5	28.5	26	27
t4	28	28	26	29	28	27	25	28	29	29	28	26
t5	28	26.5	26	29	28	27	25	28	29	28	27	26
t6	28	28.5	27	29	27	26	25	28	29	28	26	26
Average Thickness												
in mm	0.3176	0.3235	0.3118	0.3392	0.3118	0.2980	0.3108	0.3353	0.3382	0.3324	0.3078	0.3147

Note:- 1 graduand is approximately equivalent to 1 / 85 mm

Note:- 1 graduand is approximately equivalent to 1 / 85 mm

Adhesive Thickness for Each Specimen

Thickness Measurements		Specimen Number											
in graduands		9_1	9_2	9_3	9_4	9_5	9_6	10_1	10_2	10_3	10_4	10_5	10_6
t1		28	28.5	28	29	29	25	27.5	29	28	28	28	25
t2		27	28.5	27	29	28	25	28	29	29	28	26	25.5
t3		28	29	28.5	28	27.5	25.5	27.5	29.5	28	27	26	26
t4		25	28	29	28	29	27	25	28	29	29	27	27
t5		25	27.5	28	28.5	28	27.5	25	28	29	29	28	27
t6		25	27.5	28	29	29	28	25	28	28.5	28.5	27.5	26
Average Thickness													
in mm		0.3098	0.3314	0.3304	0.3363	0.3343	0.3098	0.3098	0.3363	0.3363	0.3324	0.3186	0.3069

Thickness Measurements		Specimen Number											
in graduands		11_1	11_2	11_3	11_4	11_5	11_6	12_1	12_2	12_3	12_4	12_5	12_6
t1		27.5	27	27	30	30.5	27.5	26	28	28.5	29	29	28
t2		27	28	28.5	30	29	27	26	28	29	29.5	29	28.5
t3		27	28	28	29	29	27	27	28	29	29	29.5	28
t4		24	28	28.5	29	28.5	29	24	27	27.5	29	29.5	29
t5		24	27.5	28	29	30	30	25	26	28	28.5	30	28.5
t6		24	28	29	29	29.5	30	24	27	28	29	29	29
Average Thickness													
in mm		0.3010	0.3265	0.3314	0.3451	0.3461	0.3343	0.2980	0.3216	0.3333	0.3412	0.3451	0.3353

Note:- 1 graduand is approximately equivalent to 1 / 85 mm

Adhesive Thickness for Each Specimen

Thickness Measurements		Specimen Number											
in graduands		13_1	13_2	13_3	13_4	13_5	13_6	14_1	14_2	14_3	14_4	14_5	14_6
t1		27	29	28	29	29	28	26	26	27	27	26	25
t2		27.5	28.5	28	29	29	28	26	26	27	27.5	26	25
t3		28	28	28	28	29.5	28	27	25	27.5	27	26	25
t4		27	26	27	28	28	28	25	26	27.5	27	26	26
t5		27	27	30	28	31	28	24	25.5	27	27	26	26
t6		26	27	28	29	29	29	24	26	28	27	26	27
Average Thickness													
in mm		0.3186	0.3245	0.3314	0.3353	0.3441	0.3314	0.2980	0.3029	0.3216	0.3186	0.3059	0.3020

Note:- 1 graduand is approximately equivalent to 1 / 85 mm

Length of Bond for Each Specimen

Length Measurements		Specimen Number											
in mm		1_1	1_2	1_3	1_4	1_5	1_6	2_1	2_2	2_3	2_4	2_5	2_6
L1a		9.450	9.354	9.388	9.396	9.344	9.492	9.464	9.418	9.452	9.502	9.496	9.544
L1b		9.414	9.394	9.384	9.386	9.404	9.512	9.534	9.458	9.438	9.508	9.472	9.536
L2a		9.396	9.380	9.322	9.380	9.432	9.458	9.446	9.406	9.440	9.526	9.482	9.566
L2b		9.404	9.382	9.338	9.404	9.442	9.568	9.456	9.426	9.426	9.540	9.462	9.550
Av Length		9.416	9.378	9.358	9.392	9.406	9.508	9.475	9.427	9.439	9.519	9.478	9.549

Length of Bond for Each Specimen

Length Measurements		Specimen Number										
in mm	3_1	3_2	3_3	3_4	3_5	3_6	4_1	4_2	4_3	4_4	4_5	4_6
L1a	9.422	9.288	9.342	9.462	9.422	9.432	9.488	9.474	9.418	9.586	9.552	9.602
L1b	9.424	9.286	9.348	9.438	9.442	9.380	9.458	9.448	9.422	9.554	9.528	9.556
L2a	9.408	9.224	9.340	9.476	9.412	9.404	9.414	9.444	9.416	9.504	9.540	9.562
L2b	9.402	9.258	9.378	9.452	9.406	9.386	9.514	9.450	9.430	9.512	9.540	9.600
Av Length	9.414	9.264	9.352	9.457	9.421	9.401	9.469	9.454	9.422	9.539	9.540	9.580

Length Measurements		Specimen Number										
in mm	5_1	5_2	5_3	5_4	5_5	5_6	6_1	6_2	6_3	6_4	6_5	6_6
L1a	9.532	9.450	9.498	9.566	9.242	9.580	9.408	9.428	9.558	9.484	9.540	9.614
L1b	9.638	9.436	9.496	9.428	9.418	9.572	9.422	9.392	9.564	9.556	9.528	9.526
L2a	9.514	9.444	9.484	9.430	9.434	9.772	9.522	9.436	9.540	9.420	9.550	9.524
L2b	9.488	9.458	9.454	9.584	9.414	9.606	9.424	9.468	9.546	9.462	9.638	9.520
Av Length	9.543	9.447	9.483	9.502	9.377	9.633	9.444	9.431	9.552	9.481	9.564	9.546

Length Measurements		Specimen Number										
in mm	7_1	7_2	7_3	7_4	7_5	7_6	8_1	8_2	8_3	8_4	8_5	8_6
L1a	9.320	9.142	9.556	9.424	9.476	9.410	9.508	9.498	9.428	9.504	9.404	9.420
L1b	9.318	9.136	9.564	9.418	9.478	9.448	9.524	9.516	9.446	9.524	9.404	9.418
L2a	9.336	9.308	9.524	9.406	9.500	9.502	9.472	9.500	9.472	9.548	9.134	9.360
L2b	9.348	9.300	9.528	9.404	9.472	9.472	9.502	9.502	9.456	9.526	9.152	9.336
Av Length	9.331	9.222	9.543	9.413	9.482	9.458	9.502	9.504	9.451	9.526	9.274	9.384

Length of Bond for Each Specimen

Length Measurements		Specimen Number										
in mm	9_1	9_2	9_3	9_4	9_5	9_6	10_1	10_2	10_3	10_4	10_5	10_6
L1a	9.412	9.432	9.328	9.612	9.622	9.468	9.500	9.464	9.566	9.394	9.594	9.506
L1b	9.424	9.418	9.338	9.632	9.626	9.466	9.466	9.456	9.578	9.406	9.614	9.524
L2a	9.412	9.388	9.320	9.618	9.614	9.444	9.442	9.416	9.588	9.380	9.648	9.576
L2b	9.404	9.370	9.322	9.612	9.624	9.444	9.464	9.418	9.570	9.516	9.636	9.544
Av Length	9.413	9.402	9.327	9.619	9.622	9.456	9.468	9.439	9.576	9.424	9.623	9.538

Length Measurements		Specimen Number										
in mm	11_1	11_2	11_3	11_4	11_5	11_6	12_1	12_2	12_3	12_4	12_5	12_6
L1a	9.526	9.436	9.528	9.500	9.532	9.474	9.602	9.552	9.586	9.458	9.488	9.482
L1b	9.514	9.452	9.486	9.502	9.548	9.474	9.558	9.554	9.548	9.536	9.470	9.480
L2a	9.526	9.434	9.492	9.442	9.554	9.478	9.534	9.516	9.496	9.448	9.496	9.402
L2b	9.532	9.548	9.468	9.514	9.520	9.458	9.524	9.506	9.486	9.444	9.454	9.392
Av Length	9.525	9.468	9.494	9.490	9.539	9.471	9.555	9.532	9.529	9.472	9.477	9.439

Length Measurements		Specimen Number										
in mm	13_1	13_2	13_3	13_4	13_5	13_6	14_1	14_2	14_3	14_4	14_5	14_6
L1a	9.312	9.308	9.144	9.358	9.526	9.482	9.348	9.574	9.466	9.504	9.508	9.482
L1b	9.332	9.262	9.170	9.384	9.510	9.506	9.338	9.554	9.442	9.490	9.478	9.456
L2a	9.322	9.470	9.430	9.422	9.200	9.462	9.372	9.542	9.462	9.496	9.460	9.444
L2b	9.314	9.344	9.414	9.354	9.390	9.450	9.372	9.522	9.452	9.564	9.458	9.560
Av Length	9.320	9.346	9.290	9.380	9.407	9.475	9.358	9.548	9.456	9.514	9.476	9.486

Width and Area of Bond for Each Specimen

Width Measurements		Specimen Number											
in mm		1_1	1_2	1_3	1_4	1_5	1_6	2_1	2_2	2_3	2_4	2_5	2_6
w1		25.375	25.370	25.365	25.385	25.380	25.385	25.385	25.380	25.385	25.380	25.385	25.370
w2		25.375	25.370	25.365	25.375	25.385	25.380	25.390	25.380	25.385	25.380	25.385	25.375
Av Width		25.375	25.370	25.365	25.380	25.383	25.383	25.388	25.380	25.385	25.380	25.385	25.373
Bond Area													
in sqmm		238.931	237.907	237.366	238.356	238.735	241.324	240.547	239.257	239.609	241.592	240.599	242.282

Width Measurements		Specimen Number											
in mm		3_1	3_2	3_3	3_4	3_5	3_6	4_1	4_2	4_3	4_4	4_5	4_6
w1		25.390	25.356	25.390	25.385	25.385	25.385	25.360	25.400	25.390	25.390	25.395	25.346
w2		25.390	25.357	25.390	25.390	25.390	25.390	25.365	25.395	25.390	25.390	25.395	25.350
Av Width		25.390	25.357	25.390	25.388	25.388	25.388	25.363	25.398	25.390	25.390	25.395	25.348
Bond Area													
in sqmm		238.717	234.750	238.107	239.963	238.795	238.287	241.299	240.006	239.428	241.510	242.268	243.341

Width Measurements		Specimen Number											
in graduands		5_1	5_2	5_3	5_4	5_5	5_6	6_1	6_2	6_3	6_4	6_5	6_6
w1		25.352	25.400	25.380	25.400	25.390	25.310	25.353	25.323	25.345	25.231	25.350	25.331
w2		25.352	25.400	25.390	25.400	25.390	25.319	25.357	25.323	25.340	25.229	25.355	25.333
Av Width		25.352	25.400	25.385	25.400	25.390	25.315	25.355	25.323	25.343	25.230	25.353	25.332
Bond Area													
in sqmm		240.540	240.233	239.990	243.434	239.021	243.171	238.946	239.758	241.920	238.726	244.347	241.161

Width and Area of Bond for Each Specimen

Width Measurements		Specimen Number											
in mm		7_1	7_2	7_3	7_4	7_5	7_6	8_1	8_2	8_3	8_4	8_5	8_6
w1		25.298	25.370	25.380	25.305	25.365	25.345	25.390	25.370	25.365	25.370	25.365	25.340
w2		25.300	25.370	25.370	25.302	25.370	25.335	25.390	25.370	25.365	25.370	25.365	25.345
Av Width		25.299	25.370	25.375	25.304	25.368	25.340	25.390	25.370	25.365	25.370	25.365	25.343
Bond Area													
in sqmm		236.052	233.949	242.154	238.182	240.522	239.666	241.243	241.116	239.712	241.662	235.222	237.801

Width Measurements		Specimen Number											
in mm		9_1	9_2	9_3	9_4	9_5	9_6	10_1	10_2	10_3	10_4	10_5	10_6
w1		25.356	25.390	25.390	25.390	25.390	25.390	25.353	25.351	25.385	25.385	25.390	25.351
w2		25.361	25.390	25.385	25.395	25.395	25.385	25.350	25.352	25.390	25.390	25.390	25.346
Av Width		25.359	25.390	25.388	25.393	25.393	25.388	25.352	25.352	25.388	25.388	25.390	25.349
Bond Area													
in sqmm		238.700	238.717	236.789	244.238	244.314	240.052	240.028	239.280	243.098	239.252	244.328	241.761

Width Measurements		Specimen Number											
in mm		11_1	11_2	11_3	11_4	11_5	11_6	12_1	12_2	12_3	12_4	12_5	12_6
w1		25.350	25.400	25.380	25.395	25.380	25.308	25.326	25.330	25.330	25.336	25.340	25.350
w2		25.358	25.405	25.390	25.390	25.385	25.309	25.331	25.333	25.328	25.342	25.344	25.353
Av Width		25.354	25.403	25.385	25.393	25.383	25.309	25.329	25.332	25.329	25.339	25.342	25.352
Bond Area													
in sqmm		241.484	240.498	240.992	240.962	242.111	239.697	242.001	241.460	241.360	239.998	240.166	239.293

Width and Area of Bond for Each Specimen

Width Measurements		Specimen Number											
<i>in mm</i>	13_1	13_2	13_3	13_4	13_5	13_6	14_1	14_2	14_3	14_4	14_5	14_6	
w1	25.370	25.380	25.370	25.400	25.390	25.350	25.350	25.380	25.325	25.385	25.365	25.350	
w2	25.365	25.375	25.365	25.410	25.380	25.345	25.350	25.385	25.329	25.390	25.365	25.350	
Av Width	25.368	25.378	25.368	25.405	25.385	25.348	25.350	25.383	25.327	25.388	25.365	25.350	
Bond Area													
<i>in sqmm</i>	236.425	237.178	235.651	238.286	238.784	240.168	237.213	242.352	239.479	241.524	240.359	240.457	

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Peter Chalkley and John van den Berg

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